PHYSICAL REVIEW D **72,** 017902 (2005)

Regge-trajectory analysis of $D^{\star}_{SJ}(2317)^{\pm}$, $D_{SJ}(2460)^{\pm}$ and $D_{SJ}(2632)^{+}$ mesons

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(Received 12 August 2004; published 27 July 2005)

Status of investigations of the new observed charmed strange mesons $D^{\star}_{SJ}(2317)^{\pm}$, $D_{SJ}(2460)^{\pm}$ and $D_{SJ}(2632)^{+}$ is simply reviewed. A systemic classification to these states with Regge trajectories (RTs) was made. We found that $D^{\star}_{SJ}(2317)^{\pm}$ and $D_{SJ}(2460)^{\pm}$ are reasonable to be arranged as $(0^+, 1^+)$ states, but $D_{SJ}(2632)^{+}$ seems not possible to be an orbital excited tensor particle. As a byproduct, the nonstrange charmed mesons including $D_1'(2427)$ and $D^{\star}(2637)^{+}$ were analyzed also.

DOI: 10.1103/PhysRevD.72.017902 PACS numbers: 11.55.Jy, 12.39.−x, 12.40.Nn, 14.40.Lb

The problem of quantum chromodynamics (QCD) spectrum is a central issue in nonperturbative QCD and is connected to problems of confinement and mass generation, the flavor dependence of hadron spectrum and its connection to the type of potentials are still not clear. Charmed strange meson is an important system to study hadron spectrum for its internal heavy-light quark (antiquark) components. There were limited experimental data for these mesons before, but the situation changes a lot since last year for the observation of several new states.

$D^{\star}_{SJ}(2317)^{\pm}$ was first observed in $D_S^+\pi$ by *BABAR* [1], then confirmed by CLEO [2], BELLE [3] and FOCUS [4]. This state has mass 2317.4 ± 0.9 MeV from PDG [5], about 40 MeV below DK threshold, and has full width $\Gamma < 4.6$ MeV at 90% confidence level.

$D_{SJ}(2460)^{\pm}$ was first reported by CLEO [2] in $D_S^{\star}\pi^0$ final states, and later observed by BELLE [6] and *BABAR* [7]. This state has mass 2459.3 ± 1.3 MeV [5], about 50 MeV below $D^{\star}K$ threshold, and has full width $\Gamma < 5.5$ MeV at 90% CL.

Very recently, a new surprisingly narrow charmed strange meson, $D_{SJ}(2632)^{+}$, was reported by SELEX [8] in $D_S^+\eta$ and D^0K^+ decay channels. The reported mass is 2632.6 ± 1.6 MeV, about 274 MeV and 116 MeV above D^0K^+ and $D_S\eta$ threshold, respectively. It has width $\Gamma < 17$ MeV at 90% CL. This state has an exotic relative branching ratio $\Gamma(D^0K^+)/\Gamma(D_S^+\eta) = 0.16 \pm 0.06$.

Spectrum of heavy-light system has been studied with many theoretical methods. In a unified quark model, the computed masses of charmed strange $c\bar{s}$ mesons by Godfrey-Isgur-Kokoski [9] are higher than observed experimental data. In a relativistic quark model, the orbitally and the radially excited D and B mesons was calculated [10]. The predicted masses are lower than the observed experimental data.

Lattice predicted masses spectrum of radially and orbitally excited states [11] are higher than experimental results.

In a chiral quark model [12] incorporated with heavy quark effective theory (HQET), the spectrum of corresponding excited D mesons have been calculated by W. Bardeen *et al.* [13] recently. Their results are in good agreement with experimental data.

Calculations with other methods such as QCD string, unitarized meson model, bag model and QCD sum rules [14] will not be introduced here.

Based on computations of the spectra and analyses to their decays, enormous discussions about the nature of these states have been triggered. $D^{\star}_{SJ}(2317)^{\pm}$ was explained as DK meson molecule and $D\pi$ atom [15], four quark state [16], P wave $^3P_0$ $c\bar{s}$ mesons [13,14,17], baryonium [18] and mixed state[19]. $D_{SJ}(2460)^{\pm}$ has a similar explanation except for the P wave $^1P_1$ $c\bar{s}$ explanation. $D_{SJ}(2632)^{+}$ was suggested to be a four quark state [20], tetraquarks [21] and the first radial excitation state of $D_S^{\star}(2112)^{\pm}$ [22]. A systematic review to this excited subject could be found in [23].

So far, all the calculations of hadron spectrum have relied on some models. In this paper, we will make a phenomenological analysis to these excited states by means of approximate linear structure of the RTs and will make a systemic classification to them. In fact, if the new data about these resonances has been confirmed, it is possible to study their properties of Regge trajectories (RTs).

Several decades ago, it was known from meson phenomenology that the square of the hadron masses depend approximately linearly on the spin of the hadrons, which resulted in RTs theory. A RT is a line in a Chew-Frautschi [24] plot representing the spin of the lightest particles of that spin versus their mass square, t:

$$\alpha(t) = \alpha(0) + \alpha' t, \tag{1}$$

where $\alpha(0)$, α' are intercept and slope. A RT is approximately linear, while different RTs are approximately parallel.

Based on much trial and experimentation, the flavor dependence was assumed to be on $m_1 + m_2$. A global description to RT for all flavors was constructed [25]

$$\alpha(m_1 + m_2, t) = \alpha_I(m_1 + m_2, 0) + \alpha'(m_1 + m_2)t, \tag{2}$$

where the subscript I refers to the leading trajectory.

When the mesons for which the lowest physical state is at $J = 1$ are concerned,

$$\alpha_I(m_1 + m_2, 0) = 0.57 - \frac{(m_1 + m_2)}{\mathrm{GeV}}, \quad \alpha'(m_1 + m_2) = \frac{0.9\ \mathrm{GeV}^{-2}}{[1 + 0.22(\frac{m_1+m_2}{\mathrm{GeV}})^{3/2}]}. \tag{3}$$

For light quark mesons, $\alpha' \approx 0.9\ \mathrm{GeV}^{-2}$. For leading trajectories whose ground states begin at $J = 0$, they have an intercept approximately 0.5 MeV lower and follow a similar pattern.

For radial excited light $q\bar{q}$ mesons, trajectories on (n, M^2) plots are obtained by [26]

$$M^2 = M_0^2 + (n - 1)\mu^2, \tag{4}$$

where M_0 is the mass of basic meson, n is the radial quantum number, and μ^2 (approximately the same for all trajectories) is the slope parameter of the trajectory.

Properties of RT of baryons, glueballs and hybrids [27] have also been studied.

Equation (2) was constructed from a comprehensive phenomenological analysis of available experimental data for mesonic resonances of light, medium and heavy flavors. It has been supplemented by results from various phenomenological models.

As well known, a RT may deviate from straight line, and different trajectories may deviate from parallelism [28]. The exact deviation depends on peculiar family of mesons, baryons, glueballs, hybrids and energy region. In fact, the nonlinearity and nonparallelism of RT depends on intrinsic quark-gluon dynamics including flavor and J dependence though the exact intrinsic dynamics is unknown. More detailed studies of RT have been made in many more fundamental theories [29].

However, for mesons with small J, spin-orbit contribution is not significant, once the flavor dependence is the same, intrinsic dynamics is similar. Therefore the linearity and the parallelism of RTs are kept well. In the mean time, deviation from exchange degeneracy could not be large.

Based on these analyses and Eq. (2) and (3), the linearity, the parallelism and the masses combination $m_1 + m_2$ dependence (flavor dependence) of RTs for heavy-light mesons with small J are assumed in this paper. By means of these assumptions, we start our analysis to the spectrum of mesons.

In quark model, $q\bar{q}$ mesons could be marked by their quantum numbers, $In^{2S+1}L_J$. From PDG [5], we get Table I for charmed strange mesons. In this table, entries in the first volume are observed mesons, entries in the last volume are information from PDG, entries under J^P, $n^{2S+1}L_J$ and j^P(light degrees of freedom) for those unconfirmed mesons are favored assignment by theoretical analyses.

In chiral quark model, the new observed $D^\star_{SJ}(2317)^\pm$, $D_{SJ}(2460)^\pm$ are suggested to be $(0^+, 1^+)$ states, the chiral doubler of $(0^-, 1^-)$ states: $D_S(1969)^\pm$ and $D^\star_S(2112)^\pm$. They have similar splitting $\approx$ 348 MeV:

$$D_{SJ}(2460)^\pm - D^\star_S(2112)^\pm \approx D^\star_{SJ}(2317)^\pm - D_S(1969)^\pm. \tag{5}$$

Let us check this assignment. As well known, when the deviation from exchange degeneracy is not large, the $D^\star_S(2112)^\pm$ (1^-) RT and the $D_{S2}(2573)^\pm$ (2^+) RT is almost the same and they determine a unique trajectory with slope

$$\alpha'(m_c + m_s) = \frac{1}{2.573^2 - 2.112^2}\mathrm{GeV}^{-2} \approx 0.464\ \mathrm{GeV}^{-2}. \tag{6}$$

$D_S(1969)^\pm$ (0^-) and $D_{SJ}(2460)^\pm(1^+)$ determine another trajectory with slope

$$\alpha'(m_c + m_s) = \frac{1}{2.459^2 - 1.968^2}\mathrm{GeV}^{-2} \approx 0.460\ \mathrm{GeV}^{-2}. \tag{7}$$

The slopes of two trajectories are approximately the same and two trajectories are parallel (a natural conclusion of Eq. (3)). Our simple analysis supports the assignment for mesons: $D_S(1969)^\pm$ (0^-), $D^\star_S(2112)^\pm$ (1^-), $D_{SJ}(2460)^\pm$ (1^+), $D_{S2}(2573)^\pm$ (2^+). Correspondingly, the Chew-Frautschi plots were drawn in Fig. 1.

It is found that there exists no phenomenon called as spin-orbit inversion [10,30], which may have relation with the dynamics spin-dependence of the confinement.

When the new reported $D_{SJ}(2632)^+$ is assigned as the orbitally excited $2^{+3}P_2$ state, $D^\star_S(2112)^\pm$ (1^-) and

TABLE I. Spectrum of Charmed and Strange Mesons

States	J^P	$n^{2S+1}L_J$	j^p	PDG note
$D_S(1969)^\pm$	0^-	1^1S_0	$\frac{1}{2}^-$	
$D^\star_S(2112)^\pm$	1^-	1^3S_1	$\frac{1}{2}^-$	$J^P = ?^?$ consistent with 1^-
$D^\star_{SJ}(2317)^\pm$	0^+	1^3P_0	$\frac{1}{2}^+$	J, P need confirmation
$D_{SJ}(2460)^\pm$	1^+	1^1P_1	$\frac{1}{2}^+$	
$D_{S1}(2536)^\pm$	1^+	1^3P_1	$\frac{3}{2}^+$	J, P need confirmation
$D_{S2}(2573)^\pm$	2^+	1^3P_2	$\frac{3}{2}^+$	$J^P = ?^?$ consistent with 2^+
$D_{SJ}(2632)^+$	1^-	2^3S_1	$\frac{1}{2}^-$	$J^P = ?^?$

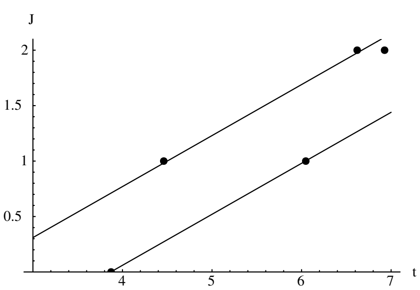

FIG. 1. Chew-Frautschi plots (t,J) for $D_S(1969)^\pm(0^-)$, $D^\star_S(2112)^\pm(1^-)$, $D_{SJ}(2460)^\pm$ (1^+) and $D_{S2}(2573)^\pm$ (2^+), where the $D_{SJ}(2632)^+$ lies outside the straight line.

$D_{SJ}(2632)^+$ (2^+) make a trajectory with slope

$$\alpha'(m_c + m_s) = \frac{1}{2.632^2 - 2.112^2}\,\mathrm{GeV}^{-2} \approx 0.405\ \mathrm{GeV}^{-2}. \tag{8}$$

The slope is much smaller than previous 0.460 GeV^{-2}. Obviously, if this assignment were right, deviation from parallelism of the two trajectories with the same flavor would be large. There is no masses dependence as Eq. (3) either. Therefore, once states $D_S(1969)^\pm$ (0^-), $D_S^\star(2112)^\pm$ (1^-) and $D_{SJ}(2460)^\pm$ (1^+) are confirmed by experiments, the assignment of $D_{SJ}(2632)^+$ as a $2^{+3}P_2$ tensor resonance seems impossible.

Now let us pay attention to the nonstrange charmed mesons. Information of the observed nonstrange charmed states are collected in Table II.

The $D^\star(2010)^\pm$ (1^-) and $D_2(2460)^\pm$ (2^+) make a trajectory with slope

$$\alpha'(m_c + m_{u,d}) = \frac{1}{2.459^2 - 2.01^2}\,\mathrm{GeV}^{-2} \approx 0.498\ \mathrm{GeV}^{-2}. \tag{9}$$

$\alpha'(m_c + m_{u,d})$ is bigger than $\alpha'(m_c + m_s)$. It is obvious that the slopes of RTs decrease with increasing quark mass, which supports the flavor dependence of Eq. (3).

$D(1869)^\pm$ is the $0^{-1}S_0$ state, but the $1^{+1}P_1$ is missing! Recently, the new observed $D_0^\star(2308)$ and $D_1'(2427)$ [31] were suggested as the $(0^+, 1^+)$ chiral doubler of $(0^-, 1^-)$ states: $D(1869)^\pm$ and $D^\star(2010)^\pm$ [23]. If $D_1'(2427)$ were the missing $1^{+1}P_1$ state, then $D(1869)^\pm$ (0^-) and $D_1'(2427)$ (1^+) would make a trajectory with slope

$$\alpha'(m_c + m_{u,d}) = \frac{1}{2.427^2 - 1.869^2}\,\mathrm{GeV}^{-2} \approx 0.417\,\mathrm{GeV}^{-2}, \tag{10}$$

which is much smaller than previous 0.498 GeV^{-2}. Obviously, this assignment of $D_1'(2427)$ is inconsistent with the approximate linearity, the parallelism and the flavor dependence of RTs. From the linearity, the parallelism and the flavor dependence of RTs, the missing $1^{+1}P_1$ state should have mass ≈ 2350 MeV.

Similar to $D_{SJ}(2632)^+$, the recently observed $D^\star(2637)^+$ by DELPHI in the $D^\star\pi\pi$ channel [32] seems impossible to be assigned as a tensor state. The Chew-Frautschi plots for these mesons were drawn in Fig. 2.

From the final states in its decay, $D_{SJ}(2632)^+$ must have $J^P = 0^+, 1^-, 2^+, \ldots$. So this state has been suggested [22] as the first radial excited state of $D_S^\star(2112)^\pm(1^-)$. $D^\star(2637)^+$ was suggested as the first radial excited states of $D^\star(2010)^\pm$ (1^-) [33]. If $D^\star(2637)^+$, $D_{SJ}(2632)^+$ are really the first radial excited states of $D^\star(2010)^\pm$ (1^-), $D_S^\star(2112)^\pm(1^-)$, their spectra are exotic: $1^{-3}S_1$ nonstrange charmed meson lies below corresponding charmed strange meson, but the first radial excited nonstrange charmed state lies above corresponding charmed strange meson. Furthermore, their trajectories on (n, M^2)-plots are not consistent with Eq. (4) for light mesons.

In conclusion, some interesting results on the charmed strange and nonstrange mesons have been obtained:

(1) The slopes of RTs decrease with increasing quark mass, which is consistent with Eq. (3).
(2) The assignment of $D_{SJ}(2460)^\pm$ as $1^{+1}P_1$ state is reasonable while the assignment of $D_1'(2427)$ as $1^{+1}P_1$ state seems impossible. The mass of the right candidate of $1^{+1}P_1$ nonstrange charmed state is predicted to have mass ≈ 2350 MeV.
(3) The assignment of $D_{SJ}(2632)^+$ and $D^\star(2637)^+$ as the $2^{+3}P_2$ state seems impossible.
(4) If $D^\star(2637)^+$, $D_{SJ}(2632)^+$ are really the first radial excited states, their spectra are exotic and their Regge behavior is different from corresponding one for light mesons.

However, when we turn back to look at the entries in Tables I and II, we find that we still have little knowledge to heavy-light charmed mesons. Quantum numbers of some states are required to be measured, or to be confirmed. Some predicted states should be searched for, and more decays modes should be detected. We hope the investigation here will be useful to further experiments.

The linearity, the parallelism and the flavor dependence of RTs have been assumed in our analysis, these properties for other mesons and possible deviations (and their origin) deserve more study. If the approximate linearity, parallelism and the flavor dependence of RTs of charmed mesons are confirmed when more experimental data are accumu-

TABLE II. Spectrum of Nonstrange Charmed Mesons

States	J^P	$n^{2S+1}L_J$	j^p	PDG note
$D(1869)^\pm$	0^-	1^1S_0	$\frac{1}{2}^-$	
$D^\star(2010)^\pm$	1^-	1^3S_1	$\frac{1}{2}^-$	J, P need confirmation
$D_0^\star(2308)^\pm$	0^+	1^3P_0	$\frac{1}{2}^+$	?
$D_1'(2427)$	1^+	1^1P_1	$\frac{1}{2}^+$	?
$D_1(2420)^0$	1^+	1^3P_1	$\frac{3}{2}^+$	J, P need confirmation
$D_2(2460)^\pm$	2^+	1^3P_2	$\frac{3}{2}^+$	$J^P = 2^+$ strongly favored
$D^\star(2637)^+$	1^-	2^3S_1	$\frac{1}{2}^-$	$J^P = ?^?$

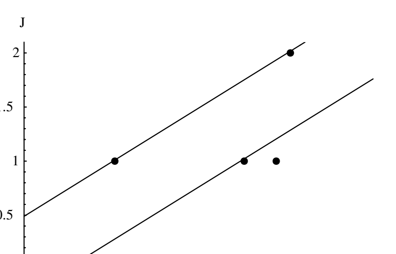

FIG. 2. Chew-Frautschi plots (t,J) for $D(1869)^\pm$ (0^-), $D^\star(2010)^\pm(1^-)$, $D_2(2460)^\pm(2^+)$ and a $1^{+1}P_1$ state ≈ 2350 MeV, where the $D_1'(2427)$ lies outside the straight line.

lated, more hints about mesons' intrinsic flavor dependence of their spectrum and about the type of confinement potential for heavy-light systems would be discerned. Furthermore, reasonable conclusions from Regge phenomenology are hoped to be incorporated into the study of quark models.

This work is supported by National Natural Science Foundation of China.

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